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METHOD FOR CHARACTERISING AN OPTICAL FIBRE LINK

10 ### Field of the invention

[0001]   The present invention is related to a method for characterising an optical fibre link by analysis of a Rayleigh backscatter signal, from which the spatial distribution of the beat length, the coupling length and

15 the PMD (Polarization Mode Dispersion) along the link can be determined.

State of the art

[0002]   The use of dispersion-shifted and dispersion

20 compensating fibres has minimised the effect of chromatic dispersion on the bandwidth of an optical link. Polarisation mode dispersion (PMD) has therefore become the most serious limiting factor in high-speed optical communication systems. There exist several measurement

25 techniques of PMD, but they only allow for measuring the global value and do not give information about the distribution of PMD along the fibre length. Measuring the spatial distribution of PMD is, however, important. Such a measurement would indeed allow to locate the bad trunks in

30 an optical link, causing high PMD value. This can be essential in the frame of a network maintenance and upgrade.

[0003]   The PMD of a fibre depends on two parameters: the beat length (L_B) and the coupling length (L_C). The beat

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length depends on the birefringence of the fibre and the coupl͜ length is related to the phenomenon of polarisation mode coupling. Measuring the spatial distribution of PMD therefore consists of measuring the
5 distribution of both the beat and coupling lengths.

[0004]   Most of the techniques proposed for measurement of the distributed PMD are based on polarisation-optical time domain reflectometry (POTDR). The concept of POTDR was introduced by A. Rogers in the 80's
10 (see A. Rogers, 'Polarization-optical time domain reflectometry: a technique for the measurement of field distributions', Applied Optics, vol. 20, pp. 1060-1074, 1981). It basically consists of measuring the polarisation properties of the Rayleigh backscatter signal when an
15 optical pulse propagates down the fibre. Some POTDR-based techniques have since been developed for PMD characterisation. Most of them allow a measurement of the beat length distribution along an optical link and, therefore, do not allow the complete determination of the
20 PMD. However, Sunnerud presented a POTDR-based set-up enabling the measurement of the accumulation of PMD along the fibre (see H. Sunnerud et al., 'Polarization-Mode Dispersion measurements along installed optical fibers using gated backscattered light and a polarimeter', J. of
25 Lightwave Technol., vol. 18, pp. 897-904, 2000). This method requires POTDR measurements at several wavelengths. A technique based on the measurement of the degree of polarisation by using a POTDR set-up has also been presented in 'Distributed detection of high-PMD sections on
30 installed fibers using a polarization-OTDR', M. Leblanc, Proc. OFMC'01, pp. 155-162, 2001, and is related to the patent application US 2003/0174312. This technique does not allow quantification of the PMD, but enables to obtain distributed information about the level of PMD. Moreover

this technique requires the complete measurement of the state of polarisation of the backscattered signal. More recently, Galtarossa described another technique for the PMD measurement for which the coupling length is determined
5 from the correlation of the birefringence vector (see 'Measurement of birefringence correlation length in long, single-mode fibers', Galtarossa et al., Opt. Lett., vol. 26, pp. 962-964, 2001), which also requires the measurement of the polarisation states of the backscattered signal.
10 Moreover, this technique requires a quite small duration of the pulses launched in the optical fibre: 5-10 ns.

[0005]   In 'Polarization mode dispersion mapping in optical fibers with a Polarization-OTDR', M. Wuilpart, G. Ravet, P. Mégret and M. Blondel, Photon. Technol. Lett.,
15 vol. 14, pp. 1716-1718, 2002, the authors describe an analysis of the POTDR signal which allows a mapping of the PMD along an optical fibre link by quantifying the PMD on each fibre of the link. The main advantage of that technique is that it does not require the complete
20 measurement of the backscattered polarisation state evolution and only uses a linear polariser at the fibre input, which is quite simple to implement. The determination of the beat length, the coupling length and finally the PMD is based on the analysis of the statistical
25 properties of the extrema present in a POTDR trace.

[0006]   In said paper by Wuilpart et al. the spatial distribution of the linear birefringence δ is characterised by a Rayleigh statistical distribution along the fibre length and it is assumed that the rate of change of the
30 birefringence angle q is described by a Gaussian distribution with zero mean and standard deviation σ depending on the polarisation mode coupling strength. The circular birefringence is neglected. The corresponding

measurement set-up is shown in Fig.1. The OTDR pulses (10 ns) externally modulate a 1553 nm DFB laser via a pulse generator and an electro-optic modulator (EOM). After amplification, the pulses are launched into the fibre

5   through an acousto-optic modulator (AOM), which suppresses the amplified spontaneous emission noise of the erbium doped fibre amplifier between two successive pulses. A linear polariser is placed at the fibre input and a polarisation controller (CP) is used to obtain the maximum

10 power after the polariser.

[0007]   Fig. 2 shows three simulated POTDR traces corresponding to the POTDR arrangement and obtained for different values of the beat length and an identical σ value. One can easily observe that the number of maxima

15 strongly depends on L_B.

[0008]   The calculation of the beat length is based on the measurement of the number of maxima of the POTDR trace. Fig.3, which has been obtained by simulation, presents the number n of maxima per unit of length in

20 function of the beat length for different values of σ. This figure shows that n varies not only with L_B but also with the strength of the polarisation mode coupling (σ). In order to estimate L_B from n, the curve corresponding to σ = 10 (the dashed curve in Fig.3) is used. This choice indeed

25 minimises the maximum possible error if one assumes that σ is smaller than 15 degrees/m. Consequently, this method allows only to give an approximate value of the beat length L_B. A relationship between the coupling length L_C and σ can be derived and one can obtain:

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$$L_C = \frac{0.879}{\sigma^2}$$

[0009]   A statistical approach is then used for determining the coupling length from the POTDR trace. Fig.

4 shows different POTDR traces that were obtained by simulation for a beat length of 25 m and for different values of σ: 2, 4 and 8 degrees/m, respectively. One can observe that the lower envelope of the curves varies in a smoother way when σ decreases and therefore when L_C increases. Defining ΔP_i as the absolute value of the difference in ordinate between two successive minima of the POTDR trace P one can write :

$$\Delta P_i = \left| P(z_i) - P(z_{i+1}) \right|$$

where z_i and z_{i+1} correspond to the distances of the ith and the $i+1^{th}$ minimum, respectively.

[0010]   A new parameter ξ can then be calculated as

$$\xi = < \Delta P_i >_i$$

where $<.>_i$ denotes the mean value for i varying from 1 to the number of minima of the POTDR trace. ξ is a measure of the speed variation of the lower envelope of the backscattered signal along the fibre length. Fig. 5 (obtained by simulation) shows the evolution of ξ according to σ for different values of the beat length L_B. The values are here expressed in dB because ξ has been calculated directly from the POTDR trace.

[0011]   The procedure for the determination of L_C is the following. From the POTDR trace, the number of maxima and each ΔP_i are measured. An approximate value of the beat length is then deduced by the method previously described and ξ is calculated by averaging ΔP_i. Finally σ can be deduced from ξ by using the curve of Fig. 5 corresponding to the correct beat length and then L_C is calculated by means of the relation $L_C=0.879/\sigma^2$ stated above. Because L_B is an approximate value, the calculated coupling length L_C will also be an approximation.

[0012]   From the measurement of the beat length and
the coupling length, it is easy to determine an approximate
value of the PMD value by

$$PMD^2 = \frac{1}{2}\left(\frac{\lambda}{cL_B}\right)^2 L_C^2 \left(\frac{2L}{L_C} - 1 + e^{-\frac{2L}{L_C}}\right)$$

5   where c is the light velocity in a vacuum, λ the
measurement wavelength and L the fibre length. It should be
emphasised that the final PMD value is approximate: this is
due to the approximation done on the beat length
measurement. This process can be repeated for each
10   contribution in the POTDR signal corresponding to the
different fibres of the optical link: it is therefore
possible to map the PMD along this link.

[0013]   The method as described above has some
important drawbacks and limitations. It only yields
15   approximate values of L_B, L_C and the PMD. Further, the
presented POTDR traces were assumed ideal. It supposes
ideal characteristics of the various components of the
experimental set-up. In practice, the set-up is
characterised by some imperfections, which cause a
20   distortion of the ideal POTDR signal. Therefore the method
as such cannot be directly applied. The POTDR signal is
also affected by noise: detector noise and residual
coherence noise, which adds a series of minima and maxima
to the POTDR trace. The final value of the measured PMD can
25   therefore be erroneous.

Aims of the invention

[0014]   The present invention aims to provide a
method for analysing a backscatter signal for determining
30   in an accurate way the spatial distribution of the beat
length, the coupling length and the polarisation mode
dispersion.

Summary of the invention

[0015]   The invention relates to a method for characterising an optical fibre link by its beat length, coupling length and polarisation mode dispersion distribution. It comprises the steps of

- sending a pulsed signal along the optical fibre link and measuring the backscattered signal (preferably a POTDR signal), after passing through a polariser,

- deriving the length of the optical fibre, the average power difference between two successive minima of the backscattered signal and the number of maxima per unit length,

- in an iterative way determining a beat length interval and an interval for the polarisation mode coupling parameter, until the length of the intervals is below a predetermined value, yielding a value for the beat length and the coupling length,

- calculating the polarisation mode dispersion.

[0016]   Preferably the POTDR signal is an ideal POTDR signal.

[0017]   Advantageously the POTDR signal is the convolution of an ideal POTDR signal and a signal depending on the pulse shape. In an alternative embodiment the POTDR signal further is convoluted with a signal taking into account the time jitter introduced by the measurement set-up.

[0018]   In a specific embodiment a smoothing algorithm is applied to the POTDR signal.

[0019]   In another object the invention relates to a method for characterising an optical link consisting of a concatenation of several fibres, wherein the method as previously described is applied to each fibre.

[0020]   The invention also relates to the use of a method as described above to locate the position of polarisation mode dispersion sources within an optical fibre link.

5   [0021]   In an advantageous embodiment the method as described is used in telecommunication networks. Alternatively, it can be applied in fibre sensing applications.

10   **Short description of the drawings**

[0022]   Fig. 1 represents the set-up for measuring a POTDR trace.

[0023]   Fig. 2 represents three simulated POTDR traces for a given σ and for different L_B values.

15   [0024]   Fig. 3 represents the number of maxima per unit length versus L_B for different values of σ.

[0025]   Fig. 4 represents simulated traces for a given beat length and different values of σ.

[0026]   Fig. 5 represents the evolution of ξ as a

20   function of σ for different values of L_B.

[0027]   Fig. 6 represents the determination of the beat length interval.

[0028]   Fig. 7 represents the determination of the interval for σ.

25   [0029]   Fig. 8 represents the distorsion of the POTDR signal due to the imperfections of the set-up (pulse shape + time jitter).

[0030]   Fig. 9 represents the evolution of n with the beat length when the imperfections of the set-up are taken

30   into account.

[0031]   Fig. 10 represents the evolution of ξ with σ when the imperfections of the set-up are taken into account.

[0032]   Fig. 11 represents the simulated and measured probability density function of Δ.

[0033]   Fig. 12 represents the window algorithm that can be used for calculated the local PMD.

Detailed description of the invention

[0034]   It is first shown how the polarisation mode dispersion from a POTDR signal can be determined in an accurate way (L_B is not approximately determined anymore) by analysing the statistical properties of its extrema. Suppose first that σ falls within the range [0,15] degrees/m, which means that the coupling length is assumed to be larger than 12.8 m. This σ interval has been chosen such that it corresponds to the values measured on real fibres.

[0035]   From a POTDR signal, the fibre length L, ξ and the number of maxima per unit of length, n_m, are easily measurable. After measuring n_m, it is possible to determine a first interval $\left[L^1_{B_{low}}, L^1_{B_{up}} \right]$ for the beat length of the fibre under test so that:

$$L_B \in \left[L^1_{B_{low}}, L^1_{B_{up}} \right]$$

$L^1_{B_{low}}$ and $L^1_{B_{up}}$ are determined by the intersections of the curves $n(L_B,\sigma)$ corresponding to $\sigma = 0$ and $\sigma = 15$ degrees/m with the straight line $n = n_m$ as shown on Fig. 6.

[0036]   When the first beat length interval is determined, the curves $\xi(\sigma,L_B)$ can be used to define an interval $\left[\sigma^1_{low}, \sigma^1_{up} \right]$ for the σ value of the fibre under test so that :

$$\sigma \in \left[\sigma^1_{low}, \sigma^1_{up} \right]$$

σ_{low}^1 and σ_{up}^1 are determined by the intersections of the curves $\xi(\sigma, L_B)$ for $L_B = L_{B_{low}}^1$ and $L_B = L_{B_{up}}^1$ with the straight line $\xi = \xi_m$, where ξ_m is the ξ value of the fibre under test measured from the POTDR signal. This principle is illustrated in Fig. 7.

[0037]   After the determination of σ_{low}^1 and σ_{up}^1, the curves $n(L_B, \sigma)$ for $\sigma = \sigma_{low}^1$ and $\sigma = \sigma_{up}^1$ can be calculated. A new beat length interval is then deduced as previously explained by Fig. 6, but using the curves obtained for $\sigma = \sigma_{low}^1$ and $\sigma = \sigma_{up}^1$ instead of $\sigma = 0$ and $\sigma = 15$ degrees/m.

[0038]   This new beat length interval denoted $\left[L_{B_{low}}^2, L_{B_{up}}^2\right]$ is included in $\left[L_{B_{low}}^1, L_{B_{up}}^1\right]$ and gives a smaller range for the beat length of the fibre under test. Fig. 7 is then used again to calculate a new σ interval $\left[\sigma_{low}^2, \sigma_{up}^2\right]$ by using the curves $\xi(\sigma, L_B)$ obtained for

$$L_B = L_{B_{low}}^2 \quad \text{and} \quad L_B = L_{B_{up}}^2$$

This new interval gives a smaller range for the σ value of the fibre under test. This process is repeated until small enough intervals are obtained for the beat length L_B and for σ.

[0039]   When the beat length L_B and σ are determined, the PMD is finally calculated by means of the relationship:

$$PMD = \sqrt{\frac{8}{3\pi}} \sqrt{\frac{1.545}{\pi}\left(\frac{\lambda}{L_B \ \sigma^2 \ c}\right)^2 \left(\frac{\sigma^2 L}{0.439} - 1 + e^{-\frac{\sigma^2 L}{0.439}}\right)}$$

[0040]   If the optical link to be characterised consists of a concatenation of several fibres, the method

is applied to each fibre of the link and their beat and coupling lengths are therefore determined independently of each other. In this way, the PMD mapping is possible along the link.

5 [0041]   The method for analysing the backscatter signal as described offers several advantages :

- it requires only the access to one end of the optical fibre link to be characterised;

- it is based on a POTDR arrangement, but does not require

10   the complete measurement of the complete state of polarisation of the backscattered signal. Only a simple polariser is required;

- it involves a POTDR measurement at only one wavelength;

- it gives accurate (not approximate) values for the beat

15   length, the coupling length and the PMD.

[0042]   In practice, the final measured signal is also affected by noise. This noise is due to the detector noise and to the presence of a residual coherence noise. As the determination of the PMD is based on the detection of

20 extrema, it is obvious that this noise will affect the results.

[0043]   As already mentioned before, the measured signal is also affected by the imperfections of the experimental set-up like the finite pulse shape and the

25 time jitter of the electronic equipment.

These phenomena (noise and imperfections of the measurement set-up) lead to a distortion of the POTDR signal. Therefore it cannot be used directly to deduce the PMD map.

The width of the optical pulses launched into the fibre

30 under test is finite and can be non-rectangular. Consequently, the backscattered power measured at the POTDR corresponds to an average of the ideal signal over a small spatial window depending on the pulse shape. The resulting

signal measured at the POTDR is in fact the convolution
product between the ideal signal and the shape of the
pulse:

$$P_{pulse}(z) = P(z) \otimes P_{shape}(z)$$

5   where $P_{pulse}(z)$ is the power measured by the POTDR according
to a certain pulse shape. $P(z)$ is the ideal POTDR signal
and $P_{shape}(z)$ is the power distribution along the pulse.
Hence the Fourier transform of $P_{pulse}(z)$ becomes:

$$P_{pulse}(k) = P(k)P_{shape}(k)$$

10   where $P_{pulse}(k)$, $P(k)$ and $P_{shape}(k)$ are the Fourier transforms
of $P_{pulse}(z)$, $P(z)$ and $P_{shape}(z)$, respectively.

[0044]   Moreover the electronic equipment is not
perfect: it is subject to a time jitter, i.e. the time
delay between two successive pulses is not constant. This
15   phenomenon strongly affects the averaging process of the
POTDR. If we suppose that the number of pulses involved in
the averaging process of the OTDR is large enough and that
the time jitter is a random variable characterised by a
Gaussian distribution of zero mean and standard deviation
20   σ_{tj}, the signal detected at the POTDR can be written as:

$$P_m(z) = P_{pulse}(z) \otimes e^{-\frac{z^2}{2\sigma_{tj}}}$$

where $P_m(z)$ is the power measured by the POTDR taking into
account the pulse shape and the time jitter. Hence the
Fourier transform of $P_m(z)$ becomes:

25          $$P_m(k) = P_{pulse}(k)\sigma_{tj}e^{-\frac{k^2\sigma_{tj}^2}{2}}$$

The pulse shape and the time jitter have for effect to
distort the measured backscattered signal. An example is
shown on Fig. 8, which has been obtained for parameters of
the experimental set-up. The signals (a) and (b) correspond

to the ideal and affected signals, respectively. One can
clearly observe that the signal is strongly distorted.

[0045]   Because of these imperfections, the method
described above cannot be used directly: the curves $n(L_B, \sigma)$
and $\xi(\sigma, L_B)$ are indeed based on ideal POTDR signals
obtained by simulations. Therefore the effects of the pulse
shape and the time jitter should be included in the
calculation of $n(L_B, \sigma)$ and $\xi(\sigma, L_B)$. In the case of the
parameters of the experimental set-up and a pulse duration
of 10 ns, these new curves are shown on Fig. 9 and 10. In
order to deduce these curves, ideal POTDR traces have been
simulated and the effects of the imperfections have been
taken into account by using the above expressions for
$P_{pulse}(z)$ and $P_m(z)$. Consequently, when the imperfections of
the experimental set-up are taken into account, the PMD map
of an optical link can still be determined. The same
reasoning as the one explained previously has to be applied
on the POTDR signal by using the new set of curves $n(L_B, \sigma)$
and $\xi(\sigma, L_B)$ described in fig. 9 and 10. As the pulse shape
is now taken into account, it is possible to launch a
larger pulse in the fibre (50 ns, for example), which will
increase the system dynamics. The maximum measurable length
will therefore be greater.

[0046]   As already indicated, the final measured
signal is also affected by noise. This noise is due to the
detector noise and the presence of a residual coherence
noise. Its main effect is to add a series of minima and
maxima to the POTDR trace. The values of n and ξ cannot
thus be correctly measured and the final calculated PMD
will be erroneous. In order to solve this problem, a
smoothing algorithm is applied to the backscattered POTDR
signal $P_m(z)$. This algorithm consists of generating the
signal $P_s(z)$ such that:

$$P_s(z) = \frac{1}{L_s} \int_{z-\frac{L_s}{2}}^{z+\frac{L_s}{2}} P_m(z')\ dz'$$

$P_s(z)$ is therefore the mean value of $P_m(z)$ on a distance interval L_s around z. The number of maxima and the distances z_k corresponding to the locations of the minima

5 of the POTDR trace are then calculated from the smoothed signal in order to ignore the influence of the small peaks generated by the noise. Afterwards, when the positions z_k are known, ξ is calculated from $P_m(z)$. When noise is present, the number of extrema of $P_s(z)$ depends of the

10 smoothing parameter L_s. So, the main problem is to choose the correct smoothing parameter to be applied to the POTDR signal.

[0047]   The location of the minima of the smoothed signal can be used to estimate the probability density

15 function of Δ, denoting the difference in z between two successive minima. This estimation can then be compared to the density probability function of Δ of a POTDR trace obtained by means of simulations taking into account the parameters L_B and σ calculated from the smoothed signal. If

20 the probability density functions of Δ obtained from $P_s(z)$ and from the simulation do not match, it means that the noise contribution is significant. The smoothing parameter L_s will therefore be chosen such that the corresponding probability density function obtained from measurements can

25 be correctly fitted by the probability density function derived from simulations: L_s is therefore chosen such that the noise contribution is reduced. Fig. 11 illustrates this concept. Figures (a), (b) and (c) show the probability density functions obtained by measurement (circles) and by

30 simulation (crosses) for a given optical fibre and for an

L_s value of 3, 4 and 5 m, respectively. One can clearly observe in this case L_s = 3 m gives the best fitting.

[0048]   The invention also provides a technique which will allow to locate more accurately the position of the PMD source within the fibre. The basic idea consists in applying the described method on a distance window (1 km, for example), which slides along the fibre length. By comparing the obtained PMD's on several successive windows as shown on Fig. 12, it is possible to locate more accurately high PMD sources within the optical fibre.

[0049]   POTDR can also be used in fibre sensing. The polarisation properties indeed depend on several external effects like strain, temperature, electric and magnetic fields. Strain, twist, temperature, electric and magnetic fields affect the birefringence within the fibre and consequently, the mean beat length. The method of the invention, which measures the spatial distribution of the beat length, therefore allows to measure the spatial distribution of these external effects after calibrating the sensing fibre.